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ANALYSIS OF THE EFFECTS ON LIFE OF LEADING-EDGE HOLES IN AN AIRFOIL SUBJECTED TO ARBITRARY SPANWISE AND CHORDWISE TEMPERATURE DISTRIBUTIONS

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16. Abstract

The effects of temperature gradients, cooling-hole rim and bulk metal temperatures, and mechanical stress were investigated by using a finite-element structural analysis of a symmetrical airfoil with and without leading-edge holes. The results indicated that leading-edge film cooling was beneficial when large chordwise temperature gradients existed and if the cooling-hole rim temperatures were above the bulk metal temperature. The effects of film cooling at other locations on the airfoil were not considered. The relative merits of convection or film cooling at the leading edge, in terms of allowable turbine inlet temperature or coolant flow requirements, were not evaluated.

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SUMMARY

The effect of leading-edge film cooling holes on the stress rupture life of a symmetrical airfoil was studied by using a finite-element structural analysis. Parameters investigated included chordwise and spanwise temperature distributions, cooling-hole rim and bulk metal temperatures, and mechanical stress. The results indicated that leading-edge film cooling was beneficial to airfoil life if the temperature at the cooling-hole rim was above the bulk metal temperature. Film cooling was especially advantageous when used to reduce large parabolic chordwise temperature gradients. The existence of high mechanical stresses or large spanwise temperature gradients made leading-edge film cooling less attractive from a life standpoint. The effects of film cooling at other locations on the airfoil were not considered. Also the relative merits of convection or film cooling at the leading edge, in terms of allowable turbine inlet temperature or coolant flow requirements, were not evaluated.

INTRODUCTION

The trend toward higher turbine inlet pressures and temperatures in aircraft gas turbines has increased utilization of film cooling, especially at the leading edges of the airfoils. Film cooling is often the only means of preventing an airfoil from overheating to the point where the strength capability of the material is inadequate for the required blade life. However, careful design is required in order to avoid the introduction of tensile thermal stresses around the holes. These stresses, in combination with tensile mechanical stresses, can reduce the potential heat-

transfer advantages of film cooling.

Only a limited amount of published information is available on the influence of the presence of film cooling holes on blade life. Furthermore, the information that is available, such as references 1 and 2, is of limited usefulness in determining the interrelation between the presence of film cooling holes and metal temperatures on life. In calculating the peak stresses at film cooling holes, references 1 and 2 make simplifying assumptions which include the use of a stress concentration factor that is independent of local temperature levels and gradients around the hole. In order to calculate the life of a film-cooled blade, it is necessary to obtain the peak stress at the holes by performing a finite-element analysis of the airfoil that is based on the temperatures at the cooling-hole rim and in the surrounding material.

The purpose of this study was to evaluate the effects on blade life of the presence of leading-edge film cooling holes for a series of arbitrarily assumed steady-state metal temperature distributions and levels and mechanical stresses. The study was based on a symmetrical airfoil geometry in order to simplify the stress analysis by avoiding the more complex temperature distributions and mechanical effects inherent in a cambered airfoil. Stress distributions, with and without leading-edge film cooling holes, were computed by using the NASA finite-element structural program NASTRAN. Since NASTRAN does not consider time-dependent effects, the predicted airfoil lives based on the computed stresses are only of qualitative significance.

The effect on airfoil life of the following parameters were investigated: chordwise and spanwise temperature distributions, cooling-hole rim and bulk metal temperatures, and applied mechanical stresses. The analyses were performed for chordwise and spanwise temperature differences from 0 to 578 K (0° to 1041° F), cooling-hole rim temperatures from 978 to 1200 K (1300° to 1700° F), and applied mechanical stresses from 0 to 20 685 N/cm^2 (0 to 30 000 psi). The stress analyses were made for a constant bulk metal temperature of 1089 K (1500° F), except for the film-cooled airfoils, where the bulk metal temperature was somewhat lower because of the cooler temperatures around the leading edge. These results were extrapolated to include the effects of increasing the bulk metal temperature to 1255 K (1800° F). Since the calculations were made for constant bulk metal temperature and assumed temperature distributions and do not consider the quantity of coolant required to reach that bulk metal temperature, the results do not constitute an evaluation of the merits of film cooling. The results are directed toward determining how film cooling

holes and the local temperature distribution around them will affect the structural integrity of a stressed airfoil.

THEORETICAL ANALYSIS

The finite-element analysis was applied to the geometry of a symmetrical airfoil specimen, shown in figure 1. This test configuration was used in the NASA thermal fatigue facility described in reference 3. The test specimen was cast from IN 100 as a hollow airfoil with a span of 10.2 cm (4.0 in.), a chord width of 5.1 cm (2.0 in.), and a constant wall thickness (except at the trailing edge) of 0.15 cm (0.06 in.). Insertable struts were used to impingement cool the airfoil, and the coolant was discharged through slots in the trailing edge.

The network of quadrilateral elements used in the finite-element stress analysis for the convection-cooled airfoil is shown in figure 2. A fine mesh was used at the leading edge because of the high stress gradients that would be expected in that region and because the width of the elements had to be kept small to simulate the curvature.

Film cooling effects on airfoil life were studied for a 0.076-cm- (0.030-in.-) diameter hole. The axis of the hole was normal to the surface of the leading edge at midspan. Only one hole was considered in order to minimize the bandwidth of the stiffness matrix and, therefore, the computing time. Figure 3 illustrates the network of triangular and quadrilateral elements around the hole.

The main heat-transfer assumptions of the analysis were (1) that the chordwise temperature distributions were parabolic, with the leading and trailing edges having the highest and identical metal temperatures at any spanwise position; (2) that the spanwise temperature distributions were parabolic, with the ends of the airfoil having the lowest and identical metal temperatures at any chordwise position; and (3) that the turbine inlet pressures were sufficiently low that the temperature gradients through the wall would be small and could be neglected. However, the last assumption is not realistic for advanced engines with high compressor pressure ratios. For these engines, according to reference 4, large wall-temperature gradients can exist in convection-cooled blades, with some metal temperatures approaching the melting point of the blade material. These gradients and high metal temperatures can be greatly reduced through the use of film cooling. There is also a

tendency in advanced engine environments for the blade trailing edge to be hotter than the leading edge. The effects of high through-the-wall temperature gradients and nonparabolic temperature distributions are beyond the scope of the present report.

The parabolic chordwise and spanwise temperature distributions which were assumed were of the form

$$T = T_0 \left[\frac{1 + c_1(x - 0.5)^2}{1 + c_2(y - 0.5)^2}\right] \tag{1}$$

where x is the nondimensionalized chord distance from the leading edge, y is the nondimensionalized span distance from the airfoil base, and c_1 and c_2 are constants defining the chordwise and spanwise gradients, respectively. The T_0 term was adjusted to maintain a constant bulk metal temperature of 1089 K (1500° F) in the convection-cooled airfoil for all cases which were considered.

In addition to these assumptions, the chordwise airfoil temperature distribution near the leading-edge hole was assumed to be parabolic from the hole rim to a distance 6 diameters downstream from the hole. At this distance the film cooling effect on the airfoil was assumed to have been dissipated. The temperature at the hole rim was set at 1089 K (1500° F) except for cases where the effect of hole rim temperature was investigated by varying this temperature above and below the bulk metal temperature. The spanwise temperature distribution in the region of the film-cooled leading edge was computed from

$$T = \frac{T_0}{1 + c_2(y - 0.5)^2}$$

with the same constant, c_2, as was used in equation (1) for the convection-cooled case. However, T_0 was adjusted so that the the calculated midspan temperature at leading edge agreed with the assumed temperature at the rim of the leading-edge hole. The cases which were analyzed are specified in table I. Chordwise and spanwise temperature distributions are shown in figure 4 for case 11. Temperature distributions for the other cases can be determined from equation (1) by using the

constants given in table I.

The computed stresses for each element were correlated in the form of effective stresses based on the von Mises distortion energy theory

$$\sigma_e = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau_{xy}^2} \tag{2}$$

where σ_e, σ_x, σ_y, and τ_{xy} are the effective, chordwise, spanwise, and shear stresses, respectively. Stress rupture lives for each element were determined for the element temperature and effective stress from the IN 100 stress rupture properties. The stress rupture properties were obtained from tests conducted on 0.15-cm- (0.06-in.-) thick tubular specimens by a NASA contractor. These data were correlated in the form

$$\sigma_e = 120.5\ P^2 - 18\ 540P + 702\ 290 \tag{3}$$

with $P = (T + 460)\ (25 + \log t)/1000$ where T is the bulk metal temperature in degrees Fahrenheit and t is the time in hours. Only elements whose maximum absolute principal stress was tensile were considered in computing stress rupture lives. It was assumed that compressive stresses could not cause failure at steady-state conditions, except for possible bowing of the trailing edge. The assumption that compressive stresses can be ignored was also used and is discussed in references 5 and 6.

Since NASTRAN does not consider creep effects, the calculated lives were only of qualitative value. In an actual blade, the element stresses would be time dependent because of stress relaxation due to creep. Stress relaxation would relieve some of the thermal stresses and increase the lives of both the film-cooled and non-film-cooled airfoils over the lives computed from the NASTRAN results.

In setting up the airfoil problem for the NASTRAN program, the airfoil end which contained mesh points 1 to 27 in figure 2 was assumed to be fixed in the span direction. The mechanical load was applied as distributed spanwise forces at the other end of the airfoil, which contained mesh points 217 to 243 (fig. 2). Restraining one end and loading the other end of the airfoil resulted in significant differences in the computed stresses and lives at these locations even though the airfoil geometry and metal temperature distributions were symmetrical in the spanwise direction. In

order to correct for the lack of stress symmetry at the ends, the computed effective stresses and lives were obtained by averaging values for symmetrical spanwise and chordwise elements.

A check of the accuracy of the analysis was obtained from the results for case 1, where the airfoil was subjected to a mechanical stress of 13 790 N/cm^2 (20 000 psi) at a uniform temperature. The stress concentration factor at the leading-edge hole, which was obtained by dividing the peak stress by the mechanical stress, was 2.99. This compares to a theoretical stress concentration factor of 3.0 for a central hole in a plate subjected to a uniaxial mechanical load.

RESULTS AND DISCUSSION

The results of the finite-element analysis of the 20 cases listed in table I are summarized in figures 5 to 9 in terms of stress rupture life as a function of various airfoil operating parameters. These results indicate that leading-edge film cooling was most beneficial where large chordwise temperature gradients existed, provided the cooling-hole rim was not cooled below the bulk metal temperature. The benefits of lower hole rim metal temperatures were outweighed by the detrimental effects of the mechanical stress concentrations and tensile thermal stresses around the holes. Since stress relaxation effects were not considered in the structural analysis, the computed lives are low, particularly where large temperature gradients exit. However, the relative trends of figures 5 to 9 are expected to be valid.

Effect of Chordwise Temperature Gradient

Figure 5 illustrates the effects of a chordwise temperature gradient on the lives of perforated and unperforated airfoils. In order to understand the significance of this figure, it should be remembered that the bulk metal temperature for the unperforated airfoils, as well as the cooling-hole rim temperature for the perforated airfoils, was maintained constant at 1089 K (1500° F). For the film cooling case (perforated airfoils) the bulk airfoil temperature was reduced slightly because of the reduction in leading-edge temperatures.

As expected, the life of the unperforated airfoil decreased because of the higher thermal stresses as the chordwise gradient increased. On the other hand, a large

chordwise gradient in the unperforated airfoil made the addition of leading-edge film cooling more advantageous because the corresponding lower leading-edge temperatures and small reduction in bulk metal temperature resulted in a significant increase in the airfoil stress rupture life. On the basis of the conditions of this analysis, leading-edge film cooling became beneficial when the unperforated airfoil had a chordwise temperature difference of 343 K (618° F) or greater.

Effect of Spanwise Temperature Gradient

Figures 6 and 7 show the effects on airfoil life of a spanwise temperature gradient both without a chordwise temperature gradient and with a chordwise temperature difference of 293 K (528° F), respectively. Both figures 6 and 7 show that, for even a relatively small spanwise temperature difference, the leading-edge film cooling holes reduced life and that the greater the spanwise temperature difference, the worse was the penalty in using film cooling.

Comparison of the results of figure 5 for a solely chordwise temperature gradient and figure 6 for a solely spanwise temperature gradient shows that for the same maximum temperature difference, spanwise temperature gradients are more detrimental to airfoil life. For a non-film-cooled airfoil with a maximum temperature difference of 111 K (200° F), a solely spanwise temperature gradient would result in a life of about 260 hours compared to a life of about 150 000 hours for a solely chordwise temperature gradient.

Effect of Temperature at Film-Cooling-Hole Rim

In figure 8, the life of a perforated airfoil with a chordwise temperature difference of 293 K (528° F) is shown as a function of the temperature at the cooling-hole rim and compared with the life of an unperforated airfoil. Figure 8 demonstrates that overcooling is detrimental to the life of a film-cooled airfoil. The buildup of tensile thermal stresses around a hole with a low rim temperature is much more harmful than the improvements in material properties from the lower metal temperature are beneficial. The presence of leading-edge holes for film cooling proved to be beneficial when the temperature at the hole rim was greater than the airfoil bulk metal temperature. In this case, the break-even point was when the hole rim tem-

perature was 1105 K (1530° F), or 17 K (30° F) above the bulk temperature.

Similar computations of stress rupture lives were made for a bulk metal temperature level of 1255 K (1800° F) by using the effective stresses determined for cases 5 and 14 to 17 but raising the bulk metal temperatures at the critical elements by 167 K (300° F). These results showed that the minimum hole rim temperature for which film cooling was beneficial was about 1228 K (1750° F), or 28 K (50° F) below the bulk temperature. This further substantiates the result that a film cooling hole is not detrimental to life if the hole rim is cooled even slightly above the bulk metal temperature. These results are also in agreement with statements made in references 1 and 2 that overcooling of film cooling or gill holes in the leading-edge region can reduce airfoil life.

Effect of Mechanical Stress

The effects of superimposed mechanical stresses on the lives of airfoils with a 293 K (528° F) chordwise temperature difference are shown in figure 9. In general, leading-edge film cooling became progressively less attractive with increasing mechanical stress because of the greater mechanical stress concentration at the cooling-hole rim.

SUMMARY OF RESULTS

The results summarized here are for a structural analysis of the effect of the presence of leading-edge holes in a symmetrical airfoil for assumed temperature distributions consistent with film-cooled airfoil designs. The comparisons are based on constant bulk metal temperature for the unperforated airfoil, and therefore represent the structural effects of the holes and the altered local temperature distributions around the holes. These results do not give an overall evaluation of the merits of film cooling.

1. The presence of leading-edge holes for film cooling was beneficial to airfoil life if the metal temperature at the hole rim was above the bulk metal temperature. If the hole rim temperature was below the bulk metal temperature, the tensile thermal stresses and the mechanical stress concentration around the hole more than offset the improved material properties that resulted from lower metal temperatures.

2. Leading-edge film cooling appeared to be most beneficial when large chordwise parabolic temperature gradients existed without film cooling.

3. Increasing spanwise temperature gradients resulted in increased penalties in utilizing leading-edge film cooling. Even for unperforated airfoils, spanwise gradients were more harmful than chordwise gradients of comparable magnitude.

4. Increasing the mechanical stress generally resulted in an increasing disadvantage for airfoils with film cooling holes as compared with unperforated airfoils, because of the greater mechanical stress concentration.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 24, 1975,
505-04.

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TABLE I. - AIRFOIL ANALYTICAL CONDITIONS

[Bulk metal temperature, 1089 K (1500° F).]

Case	Film-cooling-hole rim temperature,		Parabolic distribution constants (eq. (1))		Maximum temperature difference,		Mechanical stress,	
	K	°F	Chordwise, c_1	Spanwise, c_2	K	°F	N/cm^2	psi
1	1089	1500	0	0	0	0	13.8×10^3	20.0×10^3
2			0.4		81	145		
3			.8		103	186		
4			1.2		150	270		
5			1.6		293	528		
6			2.0		357	642		
7			0	0.04	33	59		
8				.10	79	142		
9				.20	150	270		
10			1.6	.04	327	588		
11				.10	374	674		
12				.20	448	807		
13				.40	578	1041		
14	978	1300		0	293	528		
15	1033	1400						
16	1144	1600						
17	1200	1700						
18	1089	1500					0	0
19	1089	1500					6.9	10.0
20	1089	1500					20.7	30.0

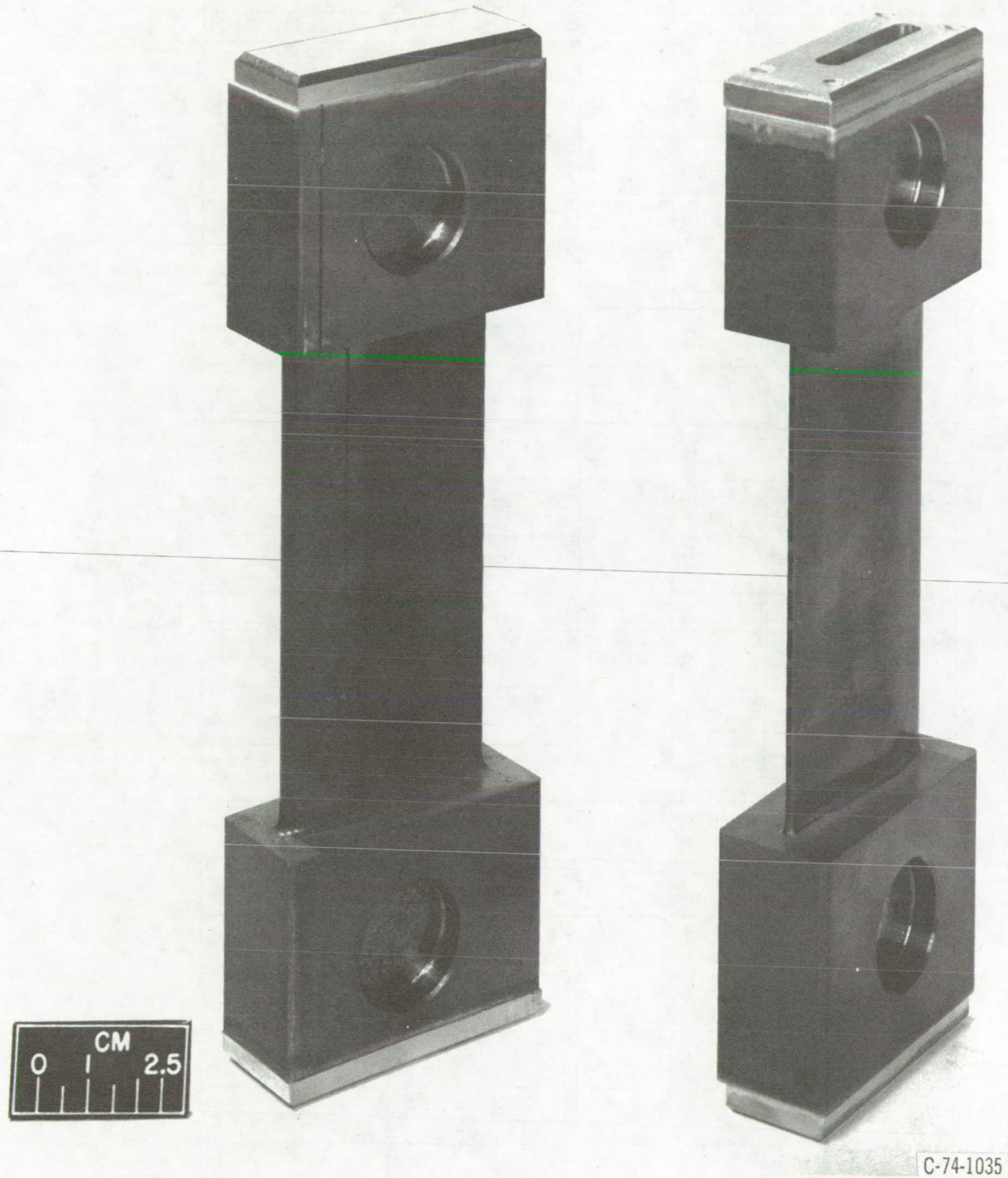


Figure 1. - Airfoil specimen.

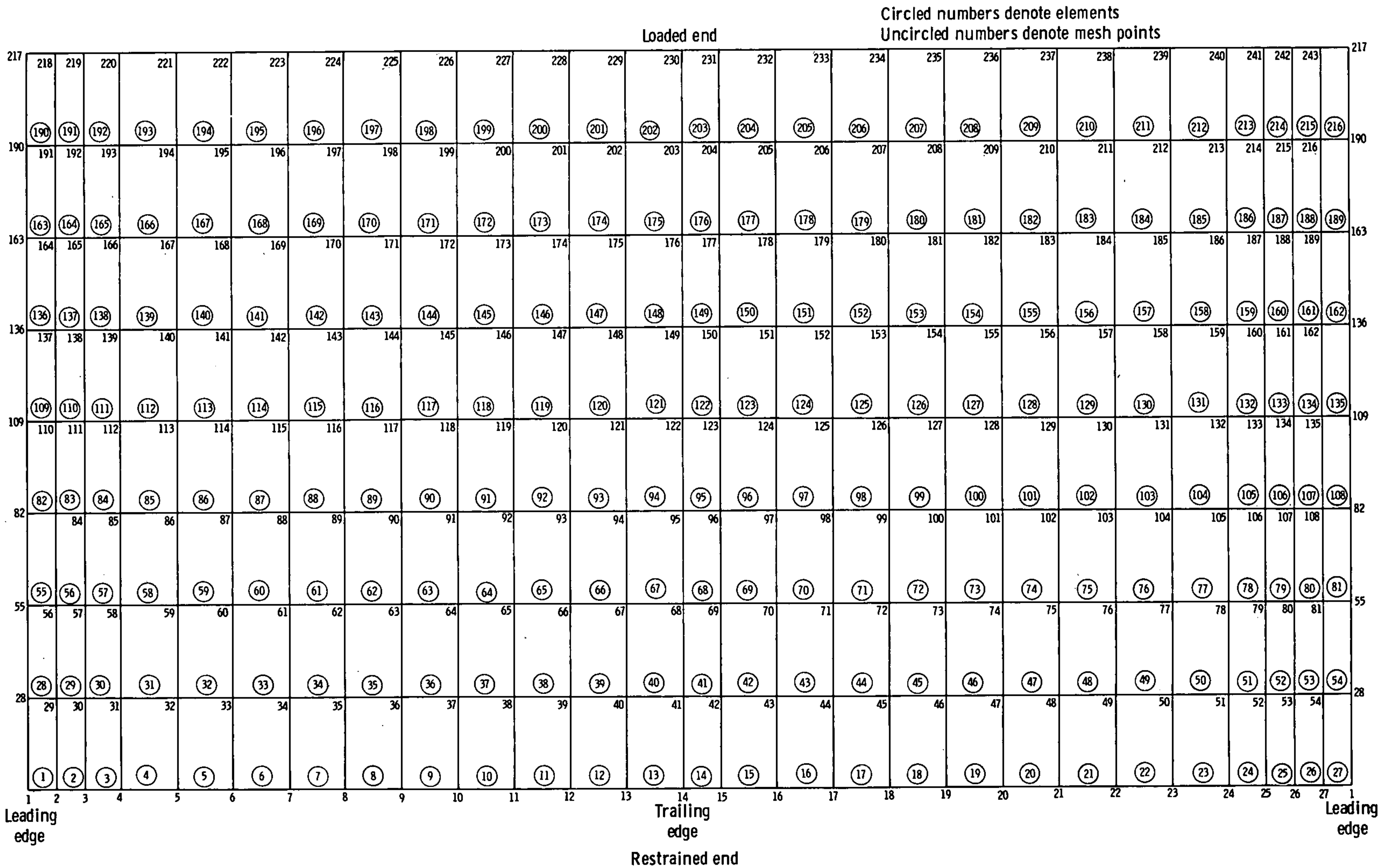


Figure 2. - Mesh network for stress analysis of basic airfoil.

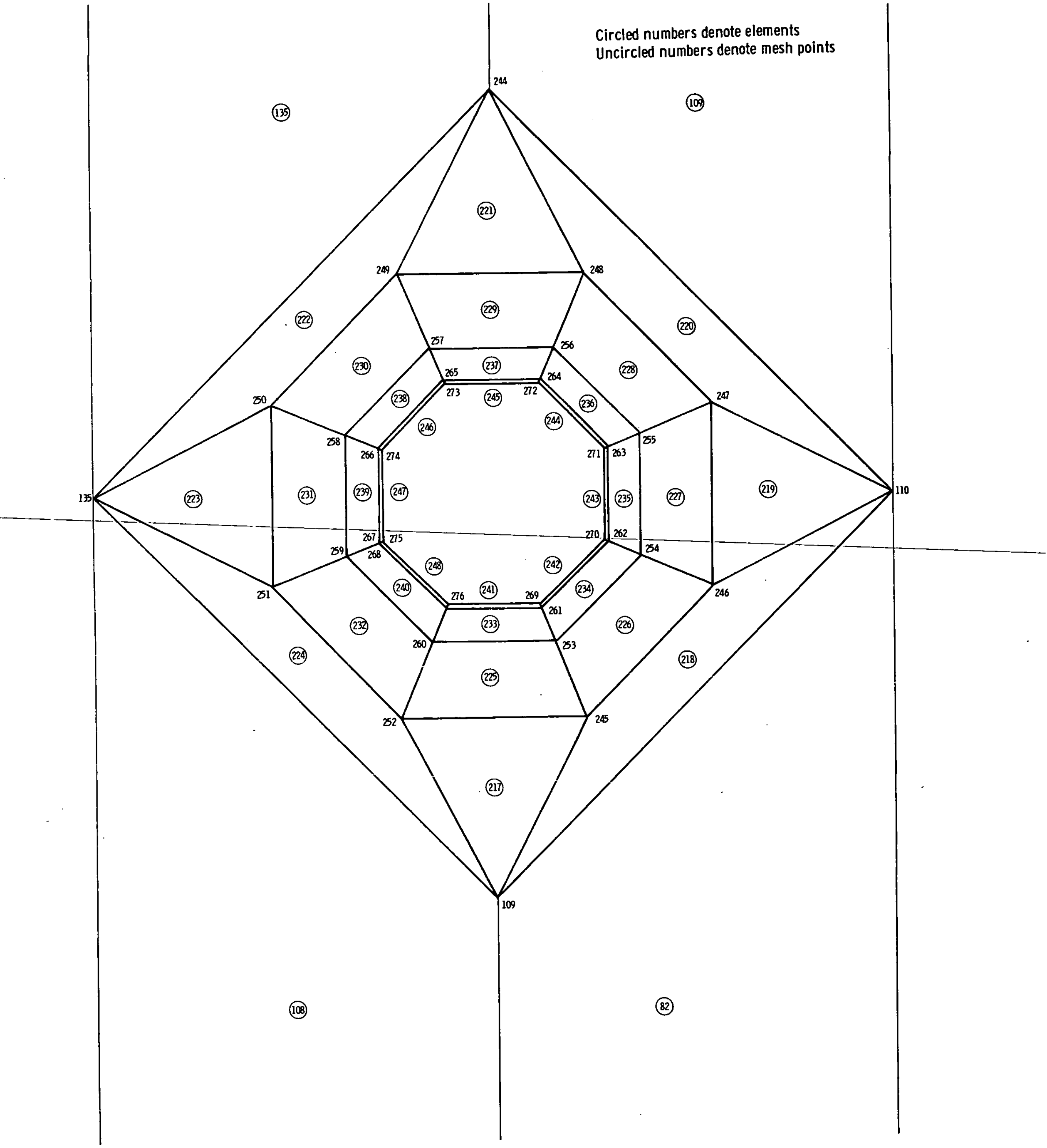
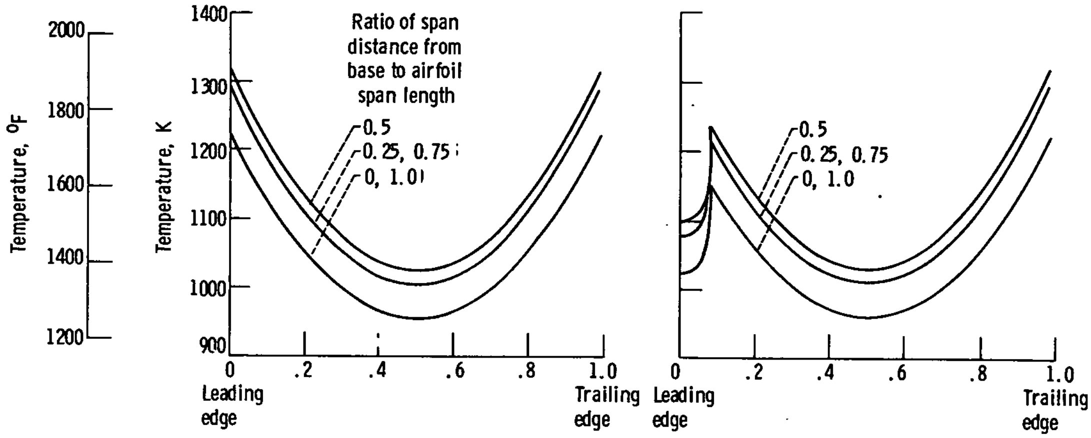


Figure 3. - Mesh network around leading-edge film cooling hole.



(a) Without leading-edge hole. (b) With leading-edge hole.

Figure 4. - Airfoil temperature distribution for case 11.

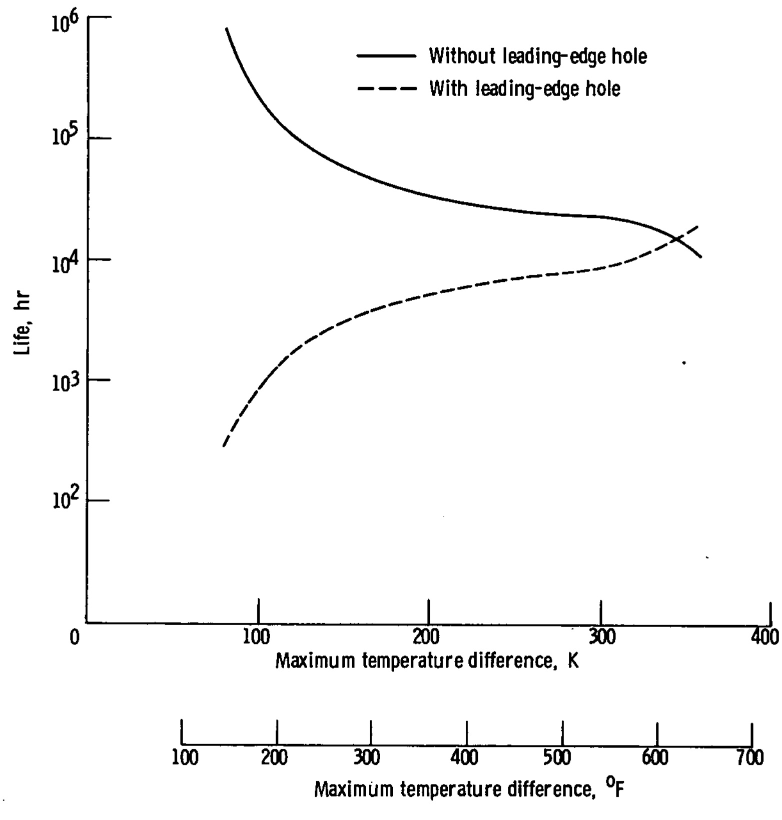


Figure 5. - Effect of chordwise temperature gradient on airfoil life with and without leading-edge film cooling with no spanwise temperature gradient (cases 2 to 6).

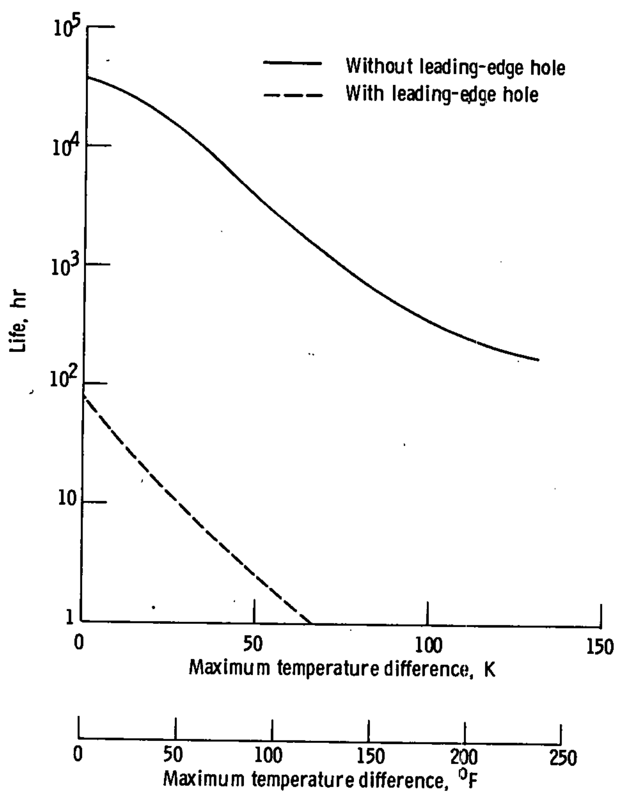


Figure 6. - Effect of spanwise temperature gradient on airfoil life with and without leading-edge film cooling with no chordwise temperature gradient (cases 1 and 7 to 9).

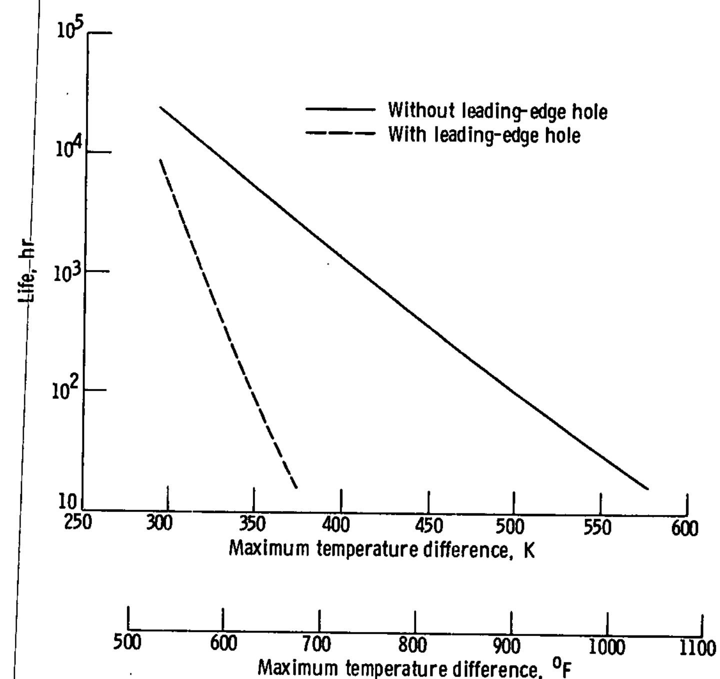


Figure 7. - Effect of spanwise temperature gradient on airfoil life with and without leading-edge film cooling with a 293 K (528 ^{o}F) chordwise temperature difference (cases 5 and 10 to 13).

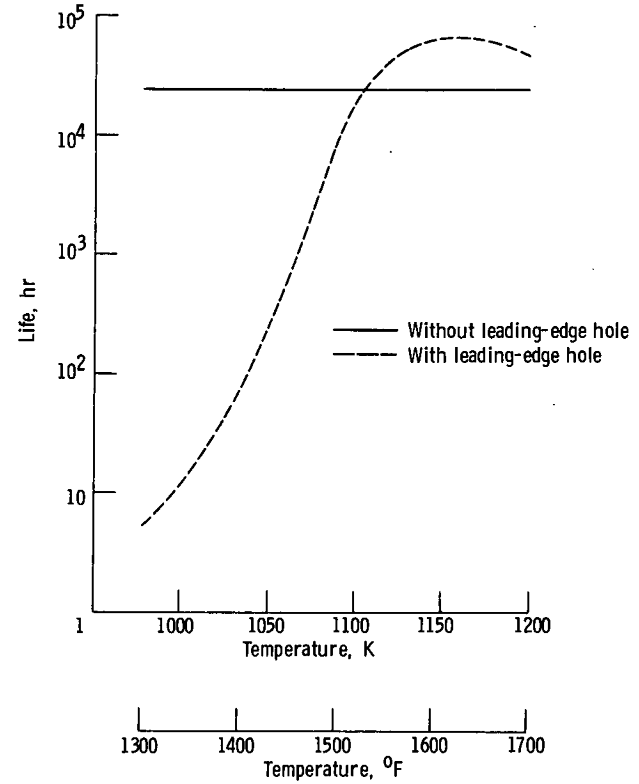


Figure 8. - Effect of temperature at cooling-hole rim on airfoil life with a 293 K (528 °F) chordwise temperature difference and no spanwise temperature gradient (cases 5 and 14 to 17).

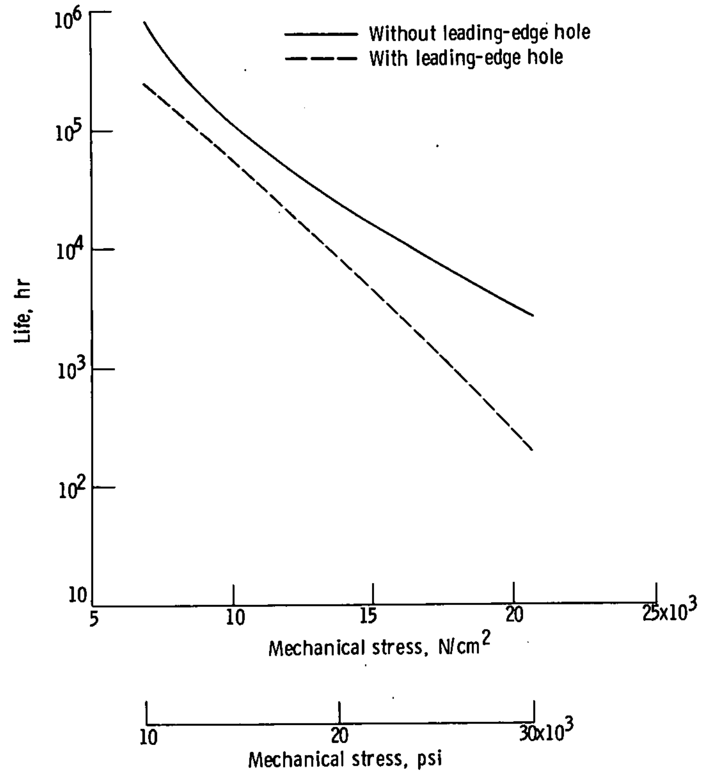


Figure 9. - Effect of mechanical stress on airfoil life with and without leading-edge film cooling with a 293 K (528°F) chordwise temperature difference and no spanwise temperature gradient.

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